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ON THE NEAR SURFACE POPULATION OF OCEANIC MICROBUBBLES

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TECHNICAL MEMORANDUM
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P.J. Mulhearn

SUMMARY (U)

A recent semi-empirical model of near-surface bubble size distributions is compared with the measurements of Walsh and Mulhearn (1987), and is shown to provide a satisfactory description, for bubble radii greater than approximately 70 μm. A strength of the method is that it can relate whitecap coverage, which is readily observable, to bubble numbers, and the former is very likely to be a better parameter than wind-speed, the normally used variable, for estimating bubble numbers.

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1. INTRODUCTION

Bubbles from breaking surface waves have a number of effects on acoustic propagation. They absorb and scatter sound and also refract it by altering the sound-speed profile. Absorption and scattering can become significant at frequencies above approximately 20 kHz. Bubbles also have a role in near-surface ambient noise, and an influence on the onset of hydrodynamic and hydoacoustic cavitation. In addition they have a strong influence on particulate matter transfer to the sea-surface, on gas transfer across the sea-surface, and on the generation of marine aerosols.

In this report the simple, semi-empirical model of Monahan (1988) for bubble size distributions just below the sea surface is compared with the experimental results of Walsh and Mulhearn (1987) and is found to provide a satisfactory explanation. There is no depth dependence in the model. Walsh and Mulhearn (1987) obtained bubble size distributions with in-situ photographic measurements, at sea.

2. BUBBLE SIZE DISTRIBUTIONS

Monahan (1988) presented a model for near-surface bubble size spectra which related the size spectrum to white-cap coverage, W, on the basis of a simple bubble-plume model which "worked backwards" from an observed relationship for the rate of marine aerosol production. This model is valid for "bubbles that reach the sea surface, burst, and produce spray droplets" (quoting Monahan (1988)). Monahan showed good agreement with experiments of Johnson and Cooke (1979), Kolovayev (1976), and Baldy and Bourgel (1985). According to the model, if N(r,o) is the near-surface concentration of bubbles with radius r, just below the sea-surface, then

$$N(r,o) = v(r)^{-1} J^{-1} P(r) H(r) W(U) \tag{1}$$

where v = a bubble's terminal rise velocity,
J = number of jet-drops produced per bursting bubble at the sea-surface, (from observations $1 < J < 5$),
P = the jet-drop fraction of the bubble-generated aerosol,
H = bubble flux to the surface within an active white-cap,
W = instantaneous fraction of the sea-surface covered by active white-caps, and
U = wind speed at 10 m elevation (ms^{-1}).

v is a function of bubble radius, but also depends on whether or not the bubbles are hydrodynamically clean or dirty. From Thorpe (1982)

$$v = 2/9\,(r^2 g/\upsilon)\,[\,(y^2 + 2y)^{1/2} - y\,], \quad \text{for dirty bubbles,}$$

where g = acceleration due to gravity,
υ = kinematic viscosity, and
y = $10.82\,\upsilon^2/gr^3$.

While for clean bubbles

$$v = 1/3\, r^2 g/\upsilon, \text{ for Reynolds Number } \approx 2r\, v/\upsilon < 0.33,$$

and

$$v = r^2 g/(\{1 - 2/[1 + (1 + 0.091\, gr^3/\upsilon)]\}18\upsilon)$$

for larger Re such that $(Re)^{-1/6} << 1$.

P, H and W are given by Monahan as:

$$P(r) = 1 - 0.715\, e^{-0.030r}, \tag{2}$$

$$H(r) = 3.13 \times 10^4 \left\{(1 + 0.057A^{1.05}) \times 10^{1.19\exp(-B\times B)}\right\} /A \tag{3}$$

where $A = (8.77 \times 10^{-2}\, r + 0.98)$,
$B = (0.380 - \log (8.77 \times 10^{-2} r + 0.98))/0.65$,

and

$$W = 3.84 \times 10^{-6}\, U^{3.41}. \tag{4}$$

Monahan obtained the expressions for P, H and W from Woolf et al (1987), Monahan (1965) and Monahan and O'Muircheartaigh (1980), respectively. The predicted range of bubble concentrations for W = 1 (i.e. a completely whitecap covered sea) is shown by the shaded region of figure 1, where the upper bound was calculated using Thorpe (1982)'s rise velocity for dirty bubbles and J = 1, and the lower bound was calculated using the rise velocity for clean bubbles and J = 5. The slope of Monahan's curves indicates an $r^{-4.3}$ dependance, approximately. During a number of the experimental runs of Walsh and Mulhearn (1987) to obtain in-situ photographic measurements of bubble size spectra at sea, some photographs were obtained which showed an extremely large number of bubbles. These were assumed to have been taken very close to a breaking wave, within a bubble "cloud". The experimental points on figure 1 are bubble size spectra from some of these "clouds". It can be seen that for two of them agreement with Monahan's model for W = 1, is satisfactory at least for larger radii. It can also be seen that the model provides an upper bound, as it should, for W = 1, if the model is valid.

Bubble-size spectra (averaged over the 32 photographs obtained in any one experimental run of 17 min duration) are presented in figures 2, 3, 4 and 5 for wind speeds of 14 ms^{-1} 11 to 13 ms^{-1}, 8 to 10 ms^{-1} and 6 to 7 ms^{-1} respectively. (From equation (4) wind speeds of 14 ms^{-1}, 11 ms^{-1}, 8 ms^{-1} and 6 ms^{-1} correspond to W's of 3%, 1.4%, 0.5% and 0.2%, respectively.) It can be seen that the experimental points scatter about Monahan's model curves. On each of figures 3 to 5 the experimental distribution averaged over the appropriate wind-speed interval is presented and reasonable agreement with Monahan's model is obtained. (One recent experiment by Tate (1987) appears to disagree with these findings in that bubble numbers considerably exceed those predicted, however the sea state encountered was much rougher than expected given the measured wind speed.)

3. DISCUSSION

The main weakness in the model is equation (4), which relates white-cap coverage, W, solely to wind-speed. W does depend on other factors and it is possible that if direct measurements of W had been obtained in the experiments of Walsh and Mulhearn (1987) better agreement would have been reached and less scatter obtained in figures 2 to 5. The regressions of bubble numbers against wind-speed (Walsh and Mulhearn (1987) found numbers $U^{3.3}$) and of W against wind-speed (see equation (4)) show considerable scatter but one would expect white-cap coverage and bubble numbers to be closely related so that W would be a superior parameter for estimating bubble populations. It is also more directly obtainable than wind-speed by remote sensing techniques.

Figures 1 to 5 also demonstrate that the numbers of bubbles with radii less than approximately 70 mm are less than Monahan's model predicts. The model is only suitable for bubbles which reach the sea-surface, burst and produce jet-drops. Smaller bubbles, which are lost by dissolution or by coalescence, before they reach the surface, are not accounted for. There are also unexplained differences between the radii of the maxima in the bubble spectra of Walsh and Mulhearn (1987), Johnson and Cooke (1979) and Kolovayev (1976). However, Monahan's model satisfactorily describes the bubble size spectra at larger radii.

Monahan (1988) does not treat the depth dependence of bubble size distributions. Due to the smallness of the current data base it is not possible to mathematically specify this too exactly. The latest attempts are those of Wu (1988) and Hall (1989). The strength of Monahan's model is that it can relate bubble size distributions to a simple, readily observable parameter - whitecap coverage. This is more satisfactory than using wind speed given the complex relationship between wind speed and sea-state. Once the near surface distribution is specified empirical curve fits or turbulent dispersion models can then be used to find the distribution of bubbles with depth.

4. CONCLUSION

For bubble radii larger than 70 μm Monahan's model provides a satisfactory description of near-surface bubble size spectra. Without coincident measurements of bubbles and whitecap coverage it is not possible to definitely say that the latter provides a better indicator of bubble numbers than wind-speed, but this does seem very likely.

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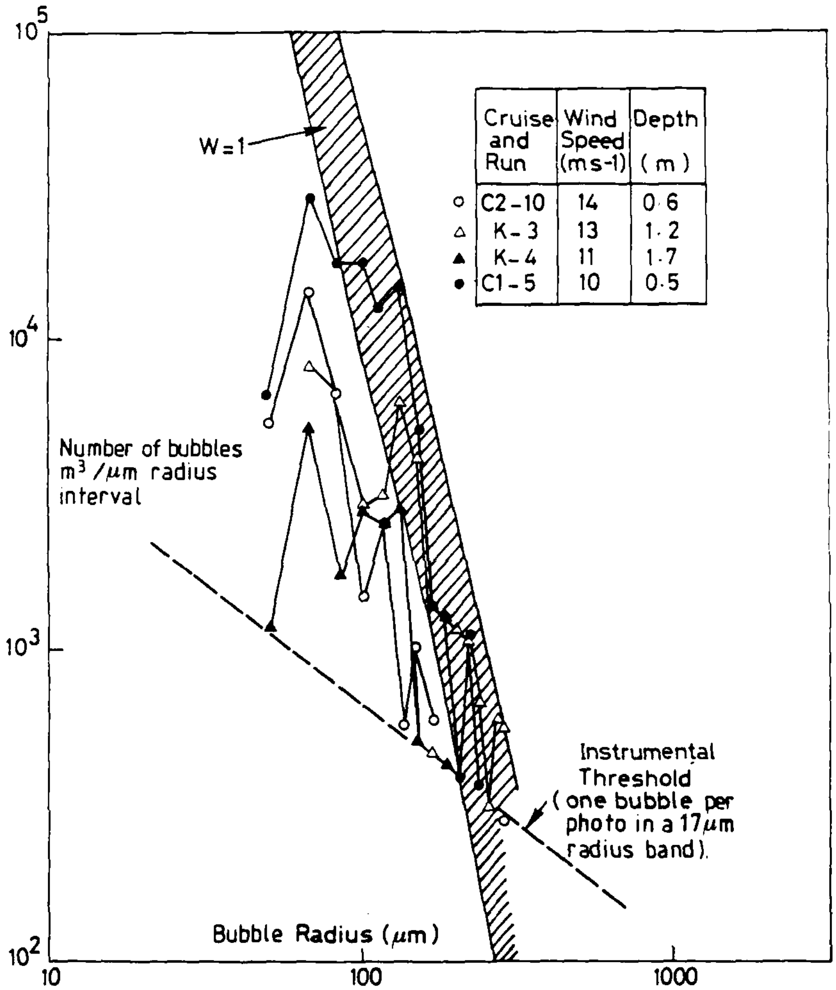

Figure 1. Bubble Cloud size distributions compared with Monahan's model for W = 1

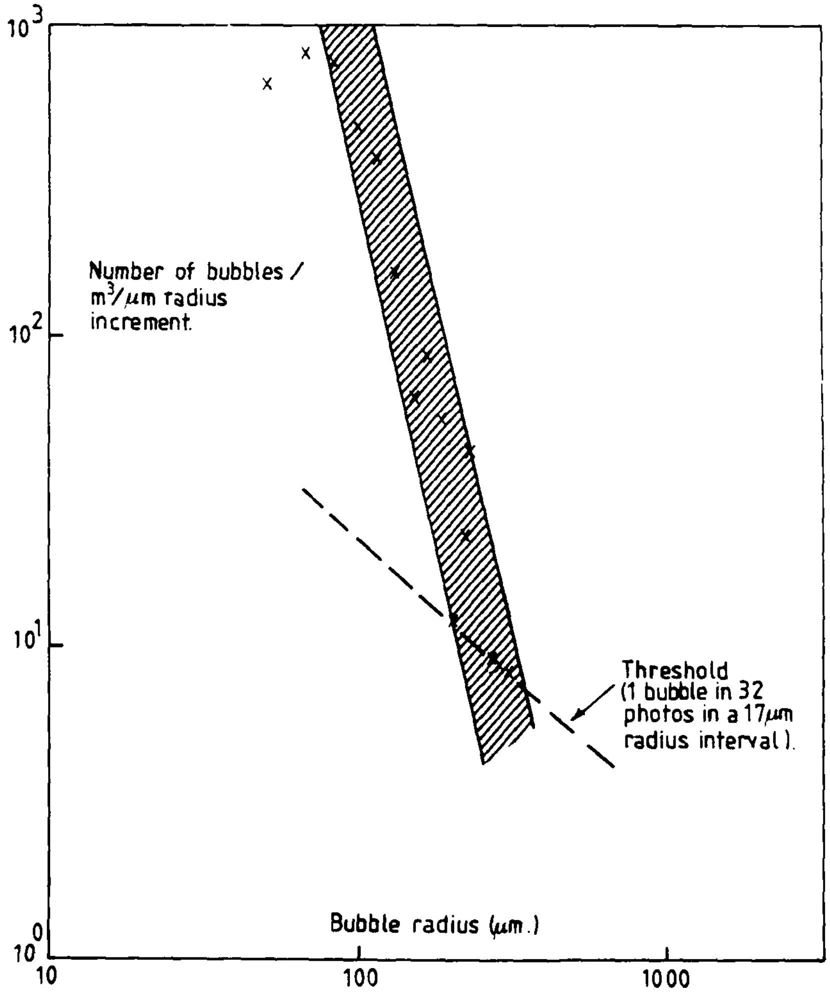

Figure 2. Bubble size distribution compared with Monahan's model for 14 ms^{-1} (run C2-10, 0.6 m depth)

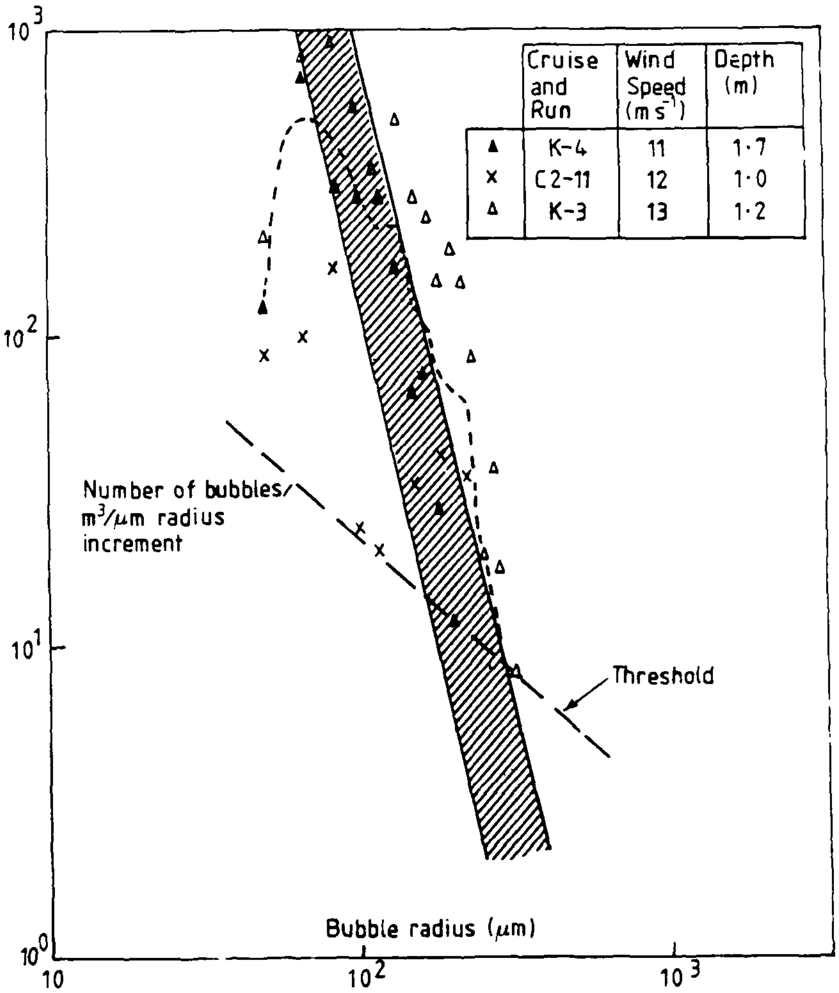

Figure 3. Bubble size distributions for 11 to 13 ms^{-1} compared with Monahan's model for 12 ms^{-1}, _ _ _ _ _ average of the 3 measured distributions

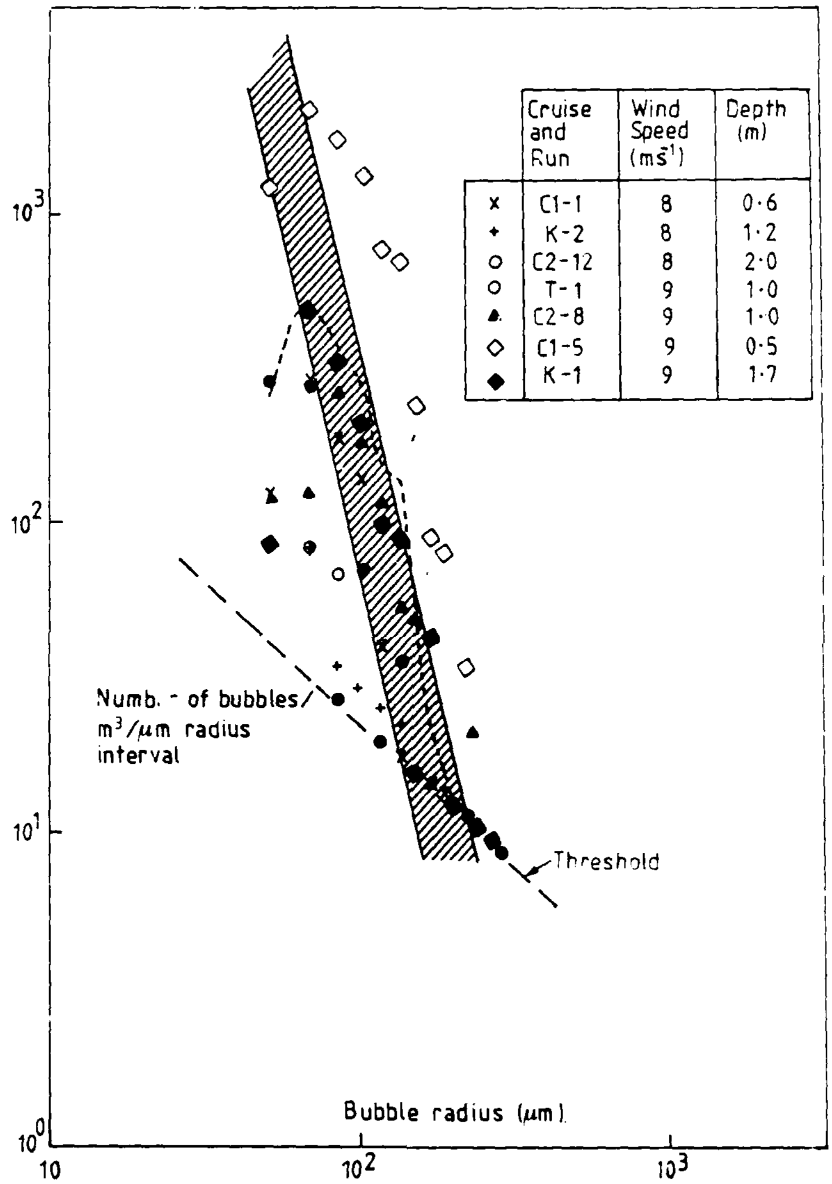

Figure 4. Bubble size distributions for 8 to 10 ms^{-1}, compared with Monahan's model for 9 ms^{-1}, - - - - -, average of the 7 measured distributions

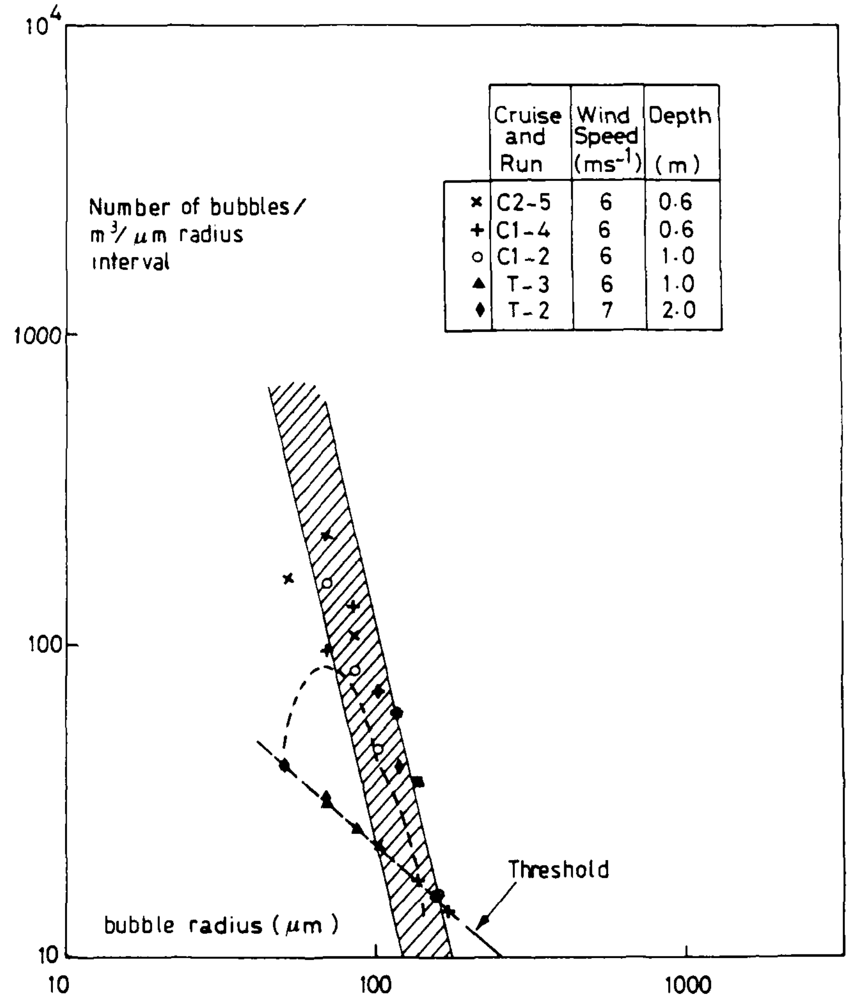

Figure 5. Bubble size distributions for 6 to 7 ms^{-1} compared with Monahan's model for 6.5 ms^{-1}, - - - - -, average of the 5 measured distributions

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